

Auto-Focus System for HDTV Field Lenses

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The operation of a contemporary high-definition television (HDTV) lens-camera for sports and special events is a multifaceted task entailing close coordination of the camera operator with a program director and utilization of honed skills in picture framing, panning, and tilting, while maintaining a sharp focus on chosen objects within complex three-dimensional scenes. The latter is made especially difficult by the absence of any true HDTV viewfinder; far higher focus sensitivity in HDTV than in standard-definition television (SDTV); and widely varying scene-lighting conditions calling for lens aperture settings that can shorten depth of field, all compounded at times by having to maintain that accurate focus on fast-moving objects within the scene. This imposes a significant strain on the camera operator, which can lead to considerable fatigue during extended shoots. This paper describes a powerful new auto-focus technology recently incorporated into two long zoom HDTV field lenses (today's zoom ranges for such lenses are on the order of 100:1 for sports coverage). The system borrows from a technology that has become central to digital still image single lens reflex cameras—called Secondary Image Registration Phase Difference technology. Sensing capabilities have been added that ensure a high accuracy in image-focus, while precisely maintaining that focus when tracking a fast-moving subject within the scene. Consistent HDTV sharpness is maintained thus freeing the camera operator to pay full attention to the important creative aspects of image framing and lens-camera positional manipulation with a lowering of fatigue.

In developing the present family of long zoom HD lenses, a first priority was image stabilization under conditions of high magnification in shooting environments that contend with undesirable physical interferences such as wind, camera platform vibrations, strong acoustic stimulations, and other such perturbations. The current highly sophisticated optical stabilization systems have been refined over some years and are testament to a variety of technologies brought to bear on this problem, as well as the many ongoing refinements born of diverse field experiences.

A more cautious approach was deemed wise in addressing any automated augmentation of the lens focus operation. Unambiguous focus is the very essence of optimized high definition and as such can never be compromised. This heightens the sensitivity of the lens-focus control and demands continuing close attention on the part of the camera operator. As camera operators grapple with the task of framing HD images and following relevant action in fast-moving sporting events, the multitasking pressures are elevated by the need for unrelenting vigilance in maintaining sharp focus. Removing this burden seemed a worthy engineering challenge.

It has long been recognized that ensuring optimized focus within the physical restrictions of the small 2/3-in. widescreen HD image format remains an industry-wide challenge to even the most experienced camera operators. HDTV inherently implies a smaller optical “permissible circle of confusion” than that of SDTV. This is especially true when the operators are simultaneously dealing with a variety of image-shaping operational dynamics while attempting to cope with the invariable sharpness limitations of even the best of contemporary HD viewfinders.

A central philosophy underlying the quest for an auto-focus (AF) system was assurance that the primary role of the camera operator could never be tampered with. Maneuvering the lens-camera system, framing the sought-for imagery, altering focal length under director instruction, selecting the scene object (from within complex scenes) of sharpest focus, are multifaceted tasks that only the camera operator can unambiguously manage.

In 2006, a prototype of the AF system was built and integrated into a long 100:1 HD zoom lens. Early technology demonstrations were conducted around the world and were specifically intended to:

- Expose the operational criteria underlying the overall system approach taken.

system was adopted in digital SLR cameras—entailing splitting off some of the light bundle being sent by the lens to the primary camera imagers. The same technique is employed in the HDTV lens herein described.

Principle of Operation of TTL Secondary Image Registration Phase Detection

The basic optical principles involved are that precise focus of the primary image plane (the HD camera's imagers) coincides with a precise focus of the two secondary images on their respective line array sensors. When in focus, a hypothetical point is in precise point focus on the HD camera's three imagers and that focus point is also precisely positioned in the center of the two-line array sensors. The physical distance between these two centers is a precise reference known to the calculating algorithm (**Fig. 1**).

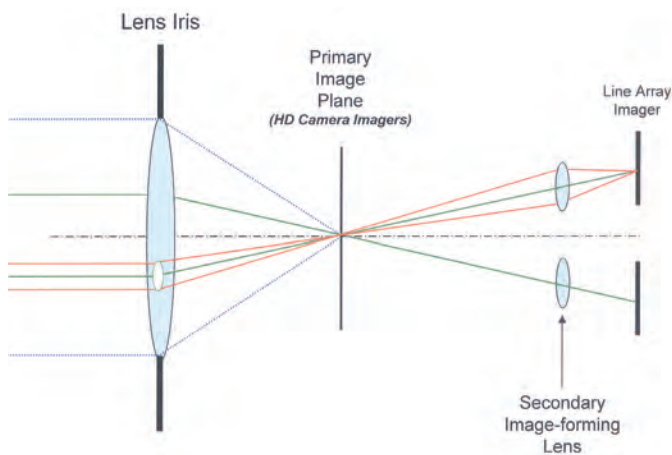


Figure 1. The main HD field lens is represented by the single large element. It focuses precisely on the object image on the HD camera's imagers. A smaller bundle of the primary light rays is passed to a second dual lens system that focuses these on to two assemblies of line array sensors.

Figure 2 outlines the action of the system for two distinct situations of primary lens defocus.

Figure 2 (a) shows the situation when the main lens-focusing element is moved to the rear. The main image is clearly defocused on the camera's imagers and at the same time the two secondary images are defocused on their respective line array imagers. Note, however, that the latter two defocused images have also moved in position—toward the outer extremities of the line arrays. The physical distance between them has increased to D_I .^{*} Knowing that distance has increased unambiguously informs the algorithm that the main lens element must be moved forward to begin the re-focusing of the image. This known pre-determination is a vital contribution to the overall speed of the system.

Similarly, when the main lens-focusing elements are positioned in the forward direction, the defocused secondary

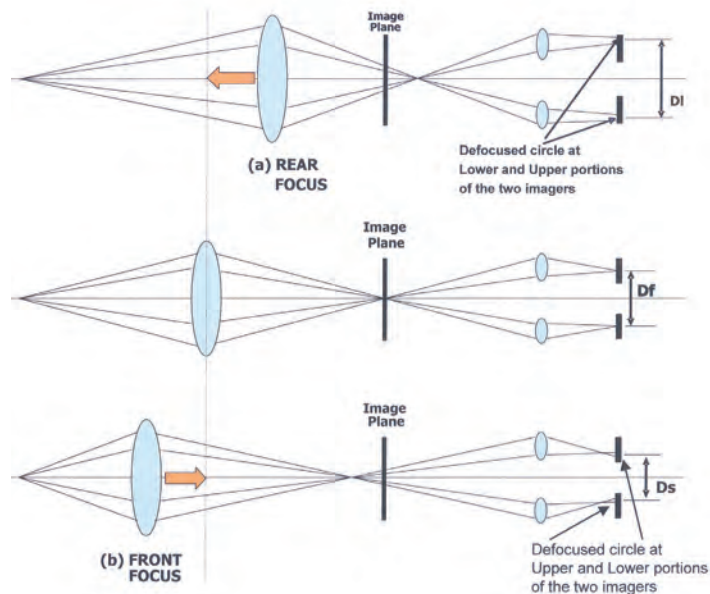


Figure 2. Relationship between the two directions of primary lens defocus and the associated alterations in physical distance between the two defocused secondary images.

images move along the line array imagers toward their inner extremities.

Now, the physical separation between the two has shortened. This, too, affords an important predetermination in that the system knows which direction to move the elements before the focus correction action is initiated.

As shown in **Fig. 3**, the in-focus position produces two high-contrast secondary images at the precise reference distance D_f .^{*} Even when grossly out of focus (in either direction), the secondary optical system is such that the detector is able to distinguish sufficient detail to allow determination of the distance between the two out-of-focus lower contrast secondary images.

Use of Array Sensors for Realtime Detection of Optical Focus

There are three aspects to detecting a selected subject within a given real-world scene:

- (1) The chosen subject may not contain much inherent detail—in which case multiple small areas need to be continually examined.
- (2) The subject may be moving in one or more of three axes—horizontal x, vertical y, and depth z—in which case sophisticated computation of the information from multiple sensors is required.
- (3) The subject may be in very fast motion—in which case the detection and associated computation needs to be as close to realtime as possible.

^{*}These designations refer to specific optical distances between the two secondary images. When the system is in precise focus that distance is designated D_f ("f" indication "focus"). When it is out of focus (Rear) we designate D_I ("I" indicating the "longest" distance between the two images). When it is out of focus in the opposite direction (Front) we designate D_s ("s" indicating the "shortest" distance between the two images).

centering of these projections on the two sensor arrays when the primary image is in precise focus.

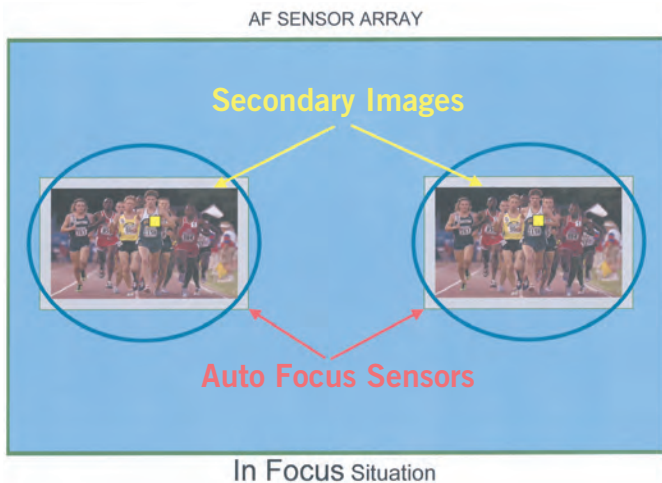


Figure 6. Illustration of the manner in which the secondary lenses project a lower light level version of the primary image onto the center of the two AF sensors.

When the primary image is defocused, the secondary images are clearly also defocused, but they have also moved in position relative to each other because of their off-axis optics. When the primary lens focusing elements are positioned to the rear, as shown earlier in **Fig. 2(a)**, the two secondary images move differentially with respect to each other, as outlined in **Fig. 7**.

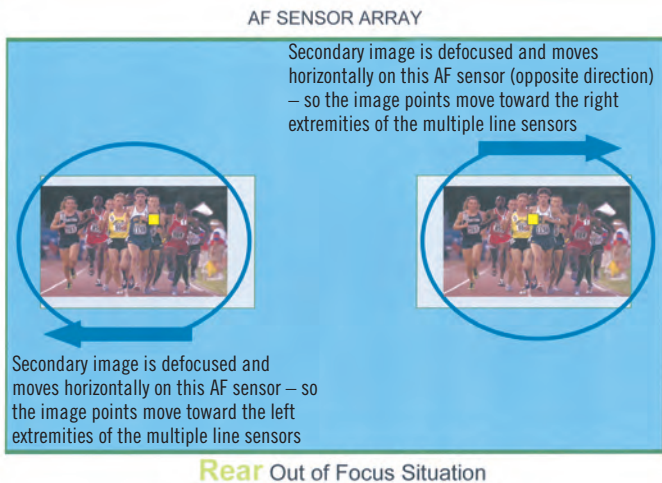


Figure 7. The differential image repositioning that is a consequence of the off-axis optical design of the secondary imaging system and is sensed by each individual array sensor.

This predictable differential repositioning of the two images is central to the effective implementation of the image phase detection mechanism outlined earlier in **Fig. 2**. **Figure 8** shows the alternative differential movement of the two projected images when the primary lens-focusing elements are positioned in front of the position for precise focus.

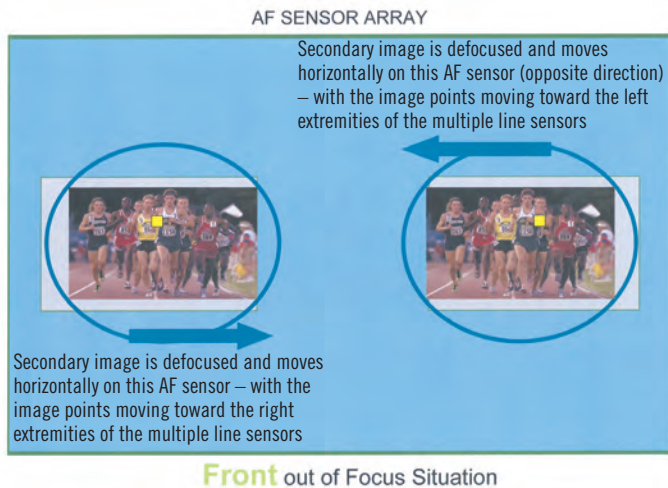


Figure 8. The differential image repositioning that is a consequence of the optical design of the secondary imaging system, and again each array sensor detects that movement in its own region of the image.

Maintaining AF on Fast Moving Subjects

Contemporary digital SLR still image cameras can shoot at increasingly higher frame rates—up to 10 frames/sec being the current state-of-the-art in the “burst” shooting favored by professional photographers. The special demand for rapid picture frame capture of selected subjects moving at a speed within a larger scene, propelled many of the continuing ingenious refinements to the phase detection AF systems seen today.

For example, if the camera is imaging a horserace with the horses coming directly toward the lens, then the temporal sampling of the camera becomes a significant factor. A fast horse will run somewhere in the vicinity of 40mph which is 59 ft in 1 sec. It means that the horse will advance 6 ft in every full frame (1/10th of a sec) of a digital SLR camera. This situation becomes far more challenging to the full motion picture scenario (60 pictures/sec capture rate) that is the essence of HDTV.

The Special Detection Requirements of a Motion Picture HDTV Camera

An auto-focus lens married to digital motion picture HD cameras can function at rates up to 60 full frame pictures per sec. This is a six times faster picture capture rate than the contemporary digital SLR still image cameras. This faster picture capture rate necessitated considerable refinements in hardware and software to contend with precision management of an AF feedback correction system for the HDTV lens. In particular, the HDTV long-zoom lens must contend with outside broadcast coverage of a wide array of sporting events—some of which can entail very fast movement as in car racing, horse and dog racing, cycling, skiing, etc. **Figure 9** depicts a small selection of the numerous sporting events that can entail extremely rapid motion of key subjects that an HDTV AF system will be required to track while maintaining accurate focus on that subject.



Figure 9. Fast motion poses a particular challenge to an HDTV AF system: A greyhound can move at up to 62 ft/sec; cyclists have been clocked at 80mph (118 ft/sec); and a racing horse at 40mph (or 59 ft/sec).

On a telephoto shot (very typical of horseracing coverage), the depth of field is quite shallow. For example, at a lens setting of 930mm and an aperture setting of f4.7 the depth of field reduces to a mere 60 ft. A subject moving at 60 ft/sec can severely tax the camera operator challenged to maintain razor sharp focus throughout the run. Experienced operators can, of course, do this—but it calls for the highest visual attention and there is a fatigue factor associated with this when operating an HDTV camera over long hours of event coverage.

In such instances, the assistance of a fast and reliable AF system was considered a potential boon to the cameraperson. But, the system needs to reliably and accurately track that horse's movement and continually update the feedback loop that maintains the focus—all in a manner that is transparent to the viewer. That requires very fast detection and rapid updating of the movement of the lens-focusing elements—ideally in far less time than it takes to formulate one frame of HD video.

Depending on the event, disposition of camera positions, operator camera movements, and director creative aspirations, motion of subjects within a scene can be combinations of vectors in all three xyz axes. The data processing associated with the multiple outputs of the individual sensors that become engaged by the moving subject can be formidable. The tremendous advantage of the array sensors is that the readout of each is extremely rapid and can furnish highly relevant information to the computational algorithm within the detection system.

Criteria for Tracking Fast Moving Subjects

To track fast-moving subjects within a busy scene, three central components of the AF control system must be optimized for high-speed operation:

- (1) The AF sensing system must deliver reliable detection information in as close to realtime as possible.
- (2) Data processing and associated computation speed of the AF algorithm must be very high.
- (3) The digital electronic circuitry and digital servo systems that drive the focusing motor controlling the optical focusing elements, must operate with high speed and high precision.

These three elements have been progressively refined and improved over generations of the EOS digital still cameras—an ever-increasing imperative for professional photographers as continuous shooting speeds have advanced to the high 10 frames/sec of current models. However, considerably greater refinements were required to meet the much higher demands of 60-field interlaced (30 frame)/sec and 60-frame progressive HDTV cameras. Fortunately, the contemporary digital servo systems in such broadcast lenses have been refined over many years to meet the continuing high realtime operational demands of creative camera operators.

Operational Control of the AF System

Because a 2-D HD image can contain many disparate objects and subjects that may be in motion relative to each other, some means of discriminating between them all is mandatory to help message the detection system as to which particular subject the camera operator has chosen for sharpest focus. This is addressed by an appropriate selection of numerous sensors deployed across the image plane. The operator selects the particular subject within a complex three-dimensional scene that is required to be in sharpest focus. This is done by operational manipulation of a box cursor in the viewfinder. This box, in turn, signals the detection system that only those sensors within the box are to be engaged in the auto-focus calculation.

The selected area for auto image focus is positioned by camera operator manual adjustments from the focus demand controller. That selected area is displayed in the camera viewfinder via digital signaling between the lens controller and the camera. The image area is indicated by a box cursor display in the viewfinder, which can be selected with one of a number of sizes via a rotary control and can be positioned via a small joystick control on the focus controller (**Fig. 10**).

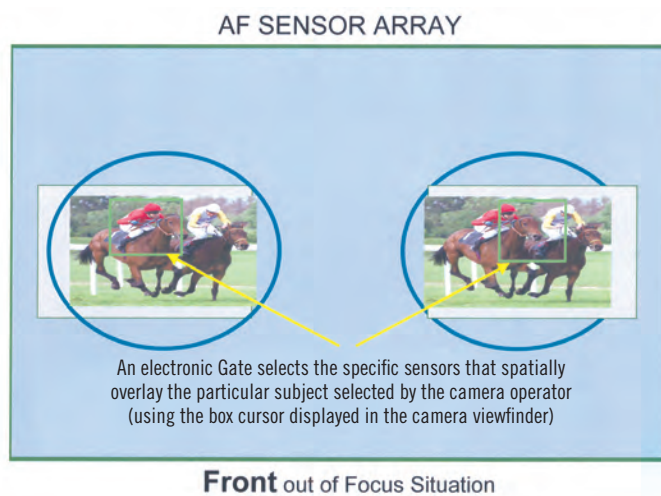


Figure 10. The role of the camera operator's box cursor is to signal the AF detection system as to which sensor groupings are engaged with the selected subject in the scene.

Implementation of TTL Secondary Image Registration Phase Detection

A modest 1/2 F-stop of light is siphoned off the main light path through the lens by a beam-splitting prism, as shown in **Fig. 11**.

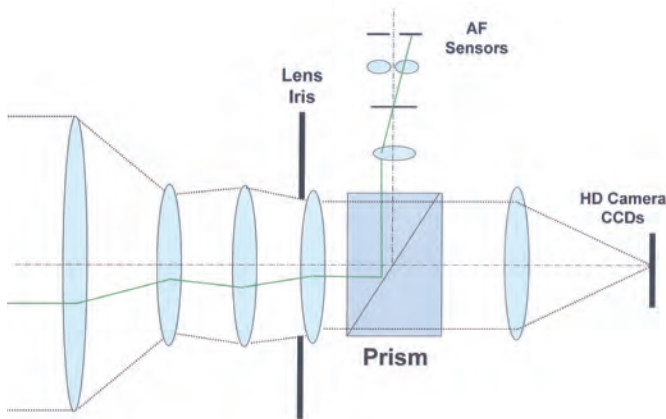


Figure 11. Illustration of the prism incorporated into the main optical path of the HD field lens to split off a sample of the through-the-lens image to the secondary imaging system for AF detection.

Placing the prism behind the lens iris ensures that it is part of the relay optic portion of the overall lens system and this allows for a smaller optical beamsplitter. The complete auto-focus control system is shown in **Fig. 12**.

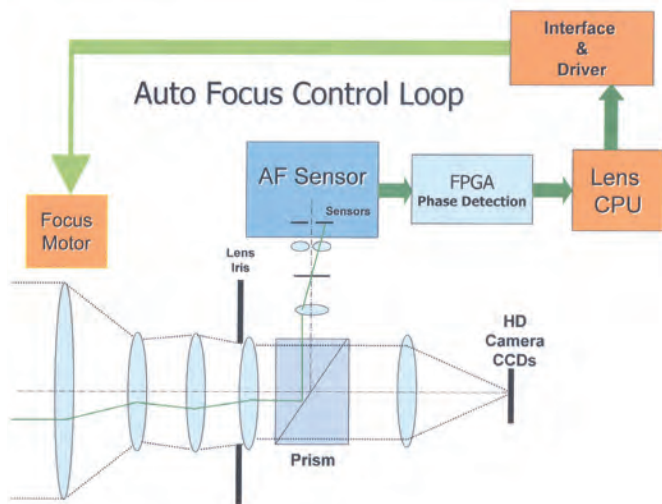


Figure 12. The overall control loop for the AF system.

Digital Servo Control System

The CPU in the HDTV field lenses must cater to all of the realtime operational needs of zooming, focusing, and aperture setting. The all-important constant angle focusing system (CAFS) places additional calculation demands on the CPU as it automatically implements the appropriate adjustments to zooming elements to correct for any alteration in angle of view created by moving the focusing elements (the traditional focus breathing problem). Over the years, the associated HDTV field lens digital servo systems have been optimized for very rapid and highly precise movements.

They both use highly precise miniature optical encoders having 16-bit resolution to provide unambiguous reporting of position to the controlling CPU. For the 100:1 lens, the full range of zoom can be completed in 0.6 sec and the full focus range in 0.8 sec. This is more than sufficient to sustain the simultaneous control of both servos during the AF operation.

Predictive Algorithm

Depending on the shooting environment (nature of the event being covered and various issues relating to the movement of subjects selected for accurate focus), the camera operator can choose the speed of operation of the control feedback control loop. This is done via a small control knob on the operator's control box.

In cases in which a high-speed control system is needed, the system is augmented by a software system that introduces a degree of prediction to the calculating algorithm. The data being provided by the array sensors convey information on vectors associated with the direction of motion, and the CPU can then extrapolate where that subject is likely to be a millisecond or two later. From this prediction, the AF CPU can issue instructions to the focus digital servo to raise its operating speed to anticipate the required new focusing position.

Conclusion

A novel new AF system integrated into an HDTV long-zoom field lens has been described. It was specifically designed to meet the highly demanding needs of full-motion HD video imaging, in which fast subject movement (as in sporting events) is frequently entailed. The heart of the system lies in an innovative AF detection system that utilizes a specially developed AF sensor providing very fast information relating to the momentary position of a rapidly moving subject within a larger scene. Secondary image registration phase detection was chosen over contrast detection because it offers unambiguous predictive information that dictates which direction the focusing elements must be moved to restore accurate focus. It also has a powerful advantage in providing reliable detection information when the subject is way out of focus. High-speed processing of the detected data combines with high-speed computation within the dedicated CPU. This in turn controls a very fast digital servo system that actuates the lens-focusing elements. The overall accuracy and speed of the AF system have proven unusually effective in many real-world field tests. It is believed that an important new augmentation of creative HDTV shooting has been achieved. The stress and fatigue associated with protracted HD coverage of long-duration sporting events—where accurate focus of selected subjects in rapid motion is a high element of value-added production—has been alleviated.

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